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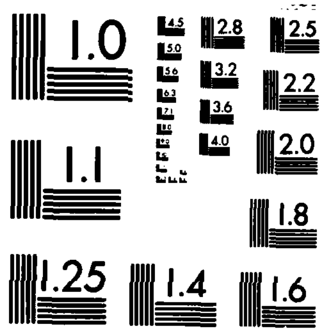

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COMPUTER APPLICATIONS IN GEOTECHNICAL ENGINEERING (CAGE) PROJECT

MISCELLANEOUS PAPER GL-85-8

CRITERIA FOR LIMIT EQUILIBRIUM SLOPE STABILITY PROGRAM PACKAGE

by

The CAGE Task Group on Slope Stability

US ARMY ENGINEER WATERWAYS EXPERIMENT STATION

May 1985

Final Report

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Washington, DC 20314-1000

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The criteria for a general limit equilibrium slope stability computer program package to define the desired capabilities and features are presented. The criteria cover the screening requirements for the evaluation of the various methods of analysis, and existing computer programs, and the desired enhancements and capabilities. The final package will be able to perform either

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a Bishop, Spencer, Modified Swedish, or Wedge analysis. The criteria are the basis of the task group decision to modify or enhance the program called UTEXAS instead of writing a new program. Until this program is completed, the following programs are recommended for interim use:

a. Bishop analysis - STABR
b. Spencer analysis - SSTAB2
c. Modified Swedish analysis - K.C.ARC
d. Wedge analysis - K.C.WEDGE

PREFACE

This paper describes the requirements for a limit equilibrium slope stability computer program that will perform analyses by either the Bishop, Spencer, Modified Swedish, or wedge methods. This work is a product of the Computer Applications in Geotechnical Engineering (CAGE) project sponsored by the Office, Chief of Engineers (OCE), US Army Corps of Engineers.

Input for the report was generated by the CAGE Task Group on slope stability. The report was compiled by Mr. Earl V. Edris, Jr., Soil Mechanics Division (SMD), Geotechnical Laboratory (GL), and revised by Mr. William E. Strohm, Jr., Engineering Geology and Rock Mechanics Division (EGRMD), GL.

Since November 1980, CAGE project work has been directed by a Policy Management Group composed of the following: Messrs. Paul Fisher, Chief, Geology Section, Geotechnical and Civil Branch (GCB), OCE (DAEN-ECE-G), Chairman; Richard Davidson, Chief, Soil Mechanics Sections, GCB, OCE; Richard Malm, Chief, Computation and Analysis Section, Engineering Support Branch, OCE (DAEN-ECE-S); Samual Gillespie, Engineer, GCB, OCE; and Leroy McAnear, Chief, SMD, WES Program Manager, Civil Works R&D Program, Materials - Soils; Dr. Don C. Banks, Chief, EGRMD, WES Program Manager, Civil Works R&D Program, Materials - Rock; and Mr. Strohm, Principal Investigator, CAGE. In June 1984 Mr. David P. Hammer, Chief, Geotechnical Branch, Engineering Division, Ohio River Division, became a member of the Policy Management Group in the place of Mr. McAnear. Development of this CAGE package was carried out under the general supervision of Dr. William F. Marcuson III, Chief, GL.

Commanders and Directors of WES during the preparation and publication of this report were COL Tilford C. Creel, CE, and COL Robert C. Lee, CE. Technical Director was Mr. Fred R. Brown.

CONTENTS

CRITERIA FOR LIMIT EQUILIBRIUM SLOPE STABILITY PROGRAM PACKAGE

PART I: INTRODUCTION

General

1. A relatively large number of slope stability computer programs have been developed in the past 20 years. The programs use a number of different procedures for computing the factor of safety. Many of the programs were developed for specific purposes and, thus, are often restricted in the range of conditions which can be analyzed. Many of the programs are not well documented. Systematic evaluation of the various programs is difficult because of their diversity, and because each requires different forms of data. Also, not all programs can be run on the same computing systems. Specific algorithms implemented in each program are not readily apparent.

Background

2. A package of standard slope stability programs will offer several benefits to the U. S. Army Corps of Engineers:

- a. A useful tool to the design engineer that will be maintained and updated by the Corps computer library will be provided.
- b. Review of District work by Divisions and a review of architectural-engineering work by Corps Districts and Divisions would be facilitated.
- c. Enable different analysis procedures in the package to be conveniently used from a common input data file.

For these reasons, the Office, Chief of Engineers, U. S. Army, directed that a task group of Corps officials and District and Division geotechnical engineers develop a slope stability package for Corps-wide use. This effort is a joint venture of Computer Applications in Geotechnical Engineering (CAGE) and the Geotechnical group of the Computer-Aided Structural Engineering project (G-CASE) with CAGE providing the leadership role.

3. The task group, formed in June 1983, consists of the following:

- a. Roger Brown, Chairman, South Atlantic Division
- b. Richard Davidson, Office, Chief of Engineers
- c. Dale Munger, Office, Chief of Engineers

d. Dave Hammer, Ohio River Division

e. David Wright, Southwest Division

f. Tom Wolff, St. Louis District

g. Franke Walberg, Kansas City District

h. Kevin Mahon, North Atlantic Division

i. Ben Foreman, Savannah District

j. Larry Cooley, Vicksburg District

k. Robert Hall, Waterways Experiment Station

l. Bill Strohm, Waterways Experiment Station

m. Earl Edris, Waterways Experiment Station

This task group used the same approach as used by the CASE task groups. Basically, existing programs are evaluated to determine the need for a new program package. If there is a need, a criteria document is developed. Interim programs are released as necessary, and ultimately a new program is written to comply with the criteria document.

4. The group realized that the need for a standard slope stability package exists. A survey of geotechnical computer programs compiled by the US Army Engineer Waterways Experment Station (WES) (Edris and Vanadit-Ellis 1982) indicated that there are 37 different programs used throughout the Corps. Thus, a criteria report was developed for a general limit equilibrium slope stability program, and existing programs were evaluated. Through this process, it became apparent that no available or existing program met all the criteria. Since modification or development of a new program would require an extensive amount of time, interim programs are recommended. The final product for the task group will be a standard slope stability package containing programs for several methods that can be selected after a one-time entry (and editing) of problem geometry, unit weights, and shear strengths. Both graphic display and tabular files of the input data and results (in sufficient detail to facilitate hand checking) will be included.

Report Organization

5. This interim report is intended to provide the field agencies with information on methods and programs being considered for the final package. The criteria are contained in Part II, while the program evaluation is documented in Part III. Part IV summarizes and describes interim programs for use until the standard program package is completed.

PART II: LIMIT EQUILIBRIUM PROGRAM CRITERIA

Introduction

6. The criteria in this part were written to define the desired capabilities and features of a general limit equilibrium slope stability computer program package. The criteria cover the screening requirements for the evaluation of the various methods of analyses, and existing computer programs and the desired computer program enhancements and capabilities. These criteria are the basis for the selection of the limit equilibrium slope stability program(s) the task group is to adopt, modify, or write for Corps-wide use. The resulting program package will be applicable to all types of geotechnical problems (i.e., cut slopes, natural slopes, surcharge loadings, and embankments for dams, levees, and roads). A detailed user's manual will be published which will discuss the data input requirements, data output options, and the theory and limitations for each analytical procedure.

Analysis Methods

General requirements

7. Analysis techniques for performing limit equilibrium slope stability analyses in two dimensions are divided into the two commonly known procedures, method of slices and wedge method. The following items were established as general criteria that must be satisfied by these procedures or programs.

a. Convenience of use. All programs must be suitable for hand checking.

b. Corps policy. One of the analysis procedures will meet the criteria set forth in EM 1110-2-1902 (US Army Corps of Engineers 1970).

c. Sudden drawdown. The program package will provide for the sudden drawdown analysis to be performed using the approach in EM 1110-2-1902, but will be independent of the mechanics (e.g., Bishop, Modified Swedish, Spencer, etc.) used to determine the factor of safety.

d. Side forces and normal forces.

(1) All procedures and programs must compute and display calculated forces (side and normal) for at least the most critical shear surface. Suitable warning messages must be displayed when negative side forces appear in the computations.

(2) One analytical procedure will not be dependent on the user specifying the side force inclination (i.e., Spencer or Morgenstern-Price procedure).

e. Equilibrium. One analysis procedure must meet all conditions of planar equilibrium.

f. Seismic. All programs will perform computations with an additional force defined by the seismic coefficient.

g. External forces. All programs must be capable of handling external forces in the form of distributed shear and normal loads. The program shall recognize the existence of structures and shall indicate when the failure surface or a slice passes through the structure.

h. Pore pressure. All programs shall have maximum flexibility for input and analysis of pore pressure data to include:

(1) Phreatic surface.

(2) Multilayer piezometric lines.

(3) Grid pore pressure.

(4) Pore pressure ratio (R_U). (Negative pore pressures will be noted with a warning message.)

i. Phreatic surface. All programs must have the capability of using a phreatic surface. The phreatic surface is used to define the boundary between the use of saturated and moist weights. The weights of soils existing below the phreatic surface will be calculated using saturated unit weights counterbalanced by the appropriate uplift force. The weights of soils existing above the phreatic surface will be calculated using moist unit weights. When a water surface exists outside the outer soil profile, the water level surface will also be used to calculate surface loads.

j. Tension cracks. All programs will be capable of handling user input for cracks in cohesive soils.

k. Factor of safety. The factor of safety (FS) is defined as the ratio of shear strength available on the shear surface to the shear strength required to reach a condition of limiting equilibrium. The factor of safety shall be represented using the Mohr-Coulomb shear strength equation.

Total stress		Effective stress
$FS = \frac{c}{S_D} + \sigma \frac{\tan \phi}{S_D}$	Equation 1	$FS = \frac{c'}{S_D} + \frac{(\sigma - u) \tan \phi'}{S_D}$
$S_D = \frac{c}{FS} + \sigma \frac{\tan \phi}{FS}$	Equation 2	$S_D = \frac{c'}{FS} + \frac{(\sigma - u) \tan \phi'}{FS}$

S_D = Shear stress required for just stable, static equilibrium; sometimes called the developed shear strength

c = Cohesion parameter from total stress analysis

c' = Cohesion parameter from effective stress analysis

σ = Normal stress

$(\sigma - u)$ = Effective normal stress where u = pore water pressure

ϕ = Angle of internal friction from total stress analysis

ϕ' = Angle of internal friction from effective stress analysis

l. Shear surfaces. The method must be able to analyze circular and noncircular shear surfaces.

m. Shear strength. Programs shall have maximum flexibility for specifying the shear strength of the soils including:

(1) Bilinear strength envelopes.

(2) Anisotropy.

(3) Strength variation with depth.

Additional requirements for the wedge method

8. The program selected for the wedge method must meet the criteria listed under general requirements plus the following:

a. Earth force inclination. The angles of inclination of the active and passive earth forces used by the analytical procedure must be independent of each other and must be variable.

b. Wedge inclination. The analytical procedure used must optimize the angle of inclination of the active and passive wedges.

c. Central block. The analytical procedure must be capable of handling an inclined central block.

Methods of analysis considered and selected

9. Methods of slices considered. The methods considered are outlined below:

a. Approximate procedure. Ordinary method of slices (also called Swedish or Fellinius).

b. Intermediate procedures.

(1) Simplified (or Modified) Bishop.

(2) Modified Swedish (also called force equilibrium, Corps of Engineers method, etc.).

c. Statically consistent procedures.

(1) Morgenstern-Price.

(2) Spencer.

(3) Sarma.

(4) Janbu (also referred to as Generalized Procedure of Slices (GPS)).

10. Methods of slices selected. No single procedure using the method of slices satisfied all of the criteria previously stated; therefore, the three following methods were selected.

a. Simplified Bishop (Bishop 1955). The Simplified Bishop method is for a circular sliding surface only and satisfies overall moment and vertical force equilibrium. A primary assumption is that interslice shear forces are zero (interslice forces are horizontal). Since the method sums forces in the vertical direction only, interslice earth forces do not enter into the analysis. The Simplified Bishop analysis has been widely used throughout the profession for many years, is relatively simple, can be checked by hand methods, and has been demonstrated to be the most accurate of all nonrigorous procedures (Johnson 1975, Soriano 1976, Whitman and Bailey 1967, Wright, Kulhawy and Duncan 1973, Wright 1969).

b. Modified Swedish (EM 1110-2-1902, US Army Corps of Engineers, 1970). The Modified Swedish method is a force equilibrium procedure satisfying vertical and horizontal force equilibrium only. A value for the inclination of the interslice earth forces must be assumed by the user, and results are sensitive to this value. A computer is required for production use, but the method is compatible to hand solution on a limited basis (i.e., for critical surfaces). The main disadvantages of this method are its sensitivity of the safety factor to the assumed inclination of the interslice earth force and the fact that it has been shown to give erroneous results for certain soil strength and geometry combinations (Soriano 1976, Wright 1969, Duncan and Wright*).

c. Spencer (Spencer 1967). The Spencer's method of analysis is a so-called "rigorous" method of analysis (i.e., satisfies all conditions of equilibrium) which assumes that the resultant interslice earth force inclination is constant for all slices and is determined by the conditions of satisfying force and moment equilibrium with the same safety factor. This method is a special case of the Morgenstern-Price method where the side force inclination is assumed constant. The Morgenstern-Price method is recognized as the most complete analysis procedure for examining stability of embankments. The Spencer method has been found by the US Bureau of Reclamation and others to be a useful, cost-effective, analysis tool for production design work. Duncan and Wright (1974) in their comparison of rigorous slope stability analysis procedures rated the Spencer's method of slices as the best of the rigorous methods. All rigorous procedures are considered too complicated for normal hand solution but the final results of Spencer's method can be hand checked (Johnson 1975, Wright 1969).

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* J. M. Duncan and S. G. Wright. 1974. "Seminar on Methods of Slope Stability Analyses," unpublished, US Army Engineer Waterways Experiment Station, Vicksburg, Miss.

11. Wedge methods considered. The following wedge methods were considered:

a. Corps wedge method as presented in EM 1110-2-1902 (US Army Corps of Engineers).

b. Lower Mississippi Valley Division (LMVD) method of planes.

12. Wedge method selected. The Corps wedge method with modification will best satisfy the criteria previously stated and therefore was selected as the method of analysis to use. Some of the more important modifications relate to the inclination of the active and passive earth forces and the use of a constant inclination of the linear active and passive wedge shear surface (i.e., active wedge shear surface does not change with soil type).

Specified Shear Surface

13. The program package shall provide the engineer the ability to analyze a specified shear surface as well as providing the option to search for a critical shear surface.

Searching

14. Searching is a systematic procedure for defining trial shear surfaces until the minimum factor of safety is determined. Several excellent procedures are available for finding critical factors of safety for wedge or arc shear surfaces. Search procedures for general shaped shear surfaces have not been adequately tested, that their use can be recommended in a routine design environment.

Critical arc analysis

15. Four commonly used procedures for searching for critical arcs are:

a. Definition of grid for center of arcs and plane of tangency of arc.

b. Definition of grid for center of arcs and maximum, minimum, and change of radii.

c. Definition of grid for center of arcs and point for intersection of trial arcs.

d. An automatic search technique in which one or more of the above techniques is used to systematically find the most critical circle.

16. All of the above procedures will be available for use with each method of slices analysis procedure. The selection of one of these search procedures will be dictated by the nature of the particular problem to be studied and/or personal preference of the engineer.

Critical wedge analysis

17. Search procedures are required to determine critical wedge inclinations associated with a defined central block. Experience has shown that satisfactory results can be obtained using a linear shear surface for the active and passive wedges. The actual soil strength of each layer will be used in the analysis procedure. The critical inclinations for the active and passive wedges must be found by iteration.

18. Since all analyses are based on a developed angle of internal friction, the critical inclination slope for the active and passive wedges will be determined for each trial factor of safety.

19. The program shall be capable of analyzing defined groups of active and passive wedge origin points as well as searching the location of critical wedge origin points by an iterative process.

Slicing and Weighing

Slicing

20. The engineer shall be allowed to control the maximum slice width or number of slices. The program will project all geometrical break points, from top of ground, soil or water profiles, onto the failure surface resulting in the normal stress across any slice being linear. All slices, except the first and last slices, shall be four-sided polygons, thus simplifying weight calculation. The slice bases which lie on a soil profile boundary must be examined for crossover of the shear surface. The crossover point is dependent upon the normal force and the determination of the lower soil shear strength of the two soils. The crossover point will be located and the single slice will be subdivided into two slices at the crossover point.

Weighing and driving forces

21. The weight and driving forces of each slice will be dependent on total unit weights, and water forces on that slice. Moist unit weights will be used above a described phreatic surface, while saturated unit weight will

be used below. The water force acting on each slice will be calculated from either phreatic, piezometric, or pore pressure data.

Numerical Analysis

22. For each method of analysis an efficient and stable convergence procedure will be used.

Mode of Operation

23. The program should be able to operate in both a time-sharing mode and in a batch mode. All data entry and data verification should be done interactively in a time-sharing mode. The user should be able to select which mode is used for calculating the safety factor based on the amount of computations and the urgency of the results.

Data Entry

24. The exact format for the data input will be developed during preparation of a user's manual. The input must be user oriented, format-free, and flexible. The same input file should work for all selected analysis procedures. The user must be able to enter data either interactively from files or commands, or by batch mode. Graphics of the input must be provided as well as the capability to edit and echo the data. Units will be pounds and feet with a metric option based on the units input for the water density. An all-quadrant coordinate system shall be used for the geometry. Slope or embankment geometry, soil profiles, material properties, phreatic and piezometric profiles, pool levels, and horizontal earthquake forces must be input separately and independently of one another. After the initial program is functional, the capability to incorporate results from other types of analyses directly into the slope stability program data file should be provided.

Data Output

25. Data output will be by printer, terminal plotter, and computer file. Exact formats will be determined later. Output will be both graphical and

tabular. Detailed slice information for the computed forces (e.g., normal force and side forces) will be provided. Warnings of unacceptable conditions such as negative side forces will be included.

26. Error messages should have enough information to guide the user toward recovery from the error. Error messages in interactive time-sharing programs should always be followed by giving the user a way to recover from the error with only a pause in the program (i.e., FORTRAN run time errors should not occur).

27. For the wedge analysis program the output shall include detailed slice information which is grouped and summed for the active, central, and passive blocks.

Graphics

28. The graphics of the input will have the ability to show the cross section to be analyzed, pore pressure data used, and the strength envelopes. The output graphics will be able to plot the section with and without the critical shear surface, surfaces analyzed, force polygon results, safety factor grid or contour, and pore pressures on the shear surface.

Equipment

29. The package programs shall be available on the Honeywell, Harris, and Control Data Corporation (CDC) computers presently used by the Corps. The package shall be convertible to whatever family of machines is selected for CEAP-IA.* The package program should be convertible for use on microcomputers using the standard FORTRAN-77 language.

Documentation

30. The programs will be well documented for the user and programmer. Selected sample problems will be included in the user's manual to illustrate the capabilities of the programs. There will be benchmark examples for each analytical procedure. The programmer's guide will define all variables and subroutines so that future enhancements can be easily made.

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* CEAP-IA is the Corps of Engineers Automation Plan, Phase IA.

Language

31. The programs will comply with the Corps of Engineers Standards of FORTRAN 77 and GCS for mainframe graphics.

PART III: EVALUATION OF EXISTING PROGRAMS

Evaluation Procedure

32. Once the major portions of the target criteria were completed, a survey of existing programs used by the Districts or available in practice was conducted. Each District evaluated all slope stability programs it currently had available according to the survey categories established by the task group. The task group members evaluated those programs that they were aware of as being available in practice but that no District was currently using. From the District responses, 34 of the 37 programs listed in WES Miscellaneous Paper GL-82-1 were reevaluated. Using the survey results, the task group selected the programs listed on the matrix shown in Table 1 as the best available for each method of analysis that satisfied the criteria. The task group then checked all the matrix answers and resolved any inconsistent replies from the initial survey.

Evaluation Categories

General

33. To evaluate the various programs, eight main categories based on the criteria described in Part II were developed. These categories are:

- a. Analysis method.
- b. General program capabilities and documentation.
- c. Input geometry.
- d. Type of failure surface.
- e. Pore pressure input.
- f. Searching options.
- g. Type and amount of output.
- h. Type of computer necessary for program.

Specific categories

34. The specific categories are outlined below:

- a. Analysis method. This category is used to indicate which method of analysis each program is able to perform. The four methods specified in the criteria section are Spencer, Bishop, Modified Swedish, and wedge method according to EM 1110-2-1902 (US Army Corps of Engineers 1970). A dot in the matrix indicates which types of analyses the program is able to perform.

b. General program capabilities and documentation. This category is used to indicate if the program is documented and if it can handle certain conditions. Documentation includes the availability of a user's manual and program documentation. The ability to interactively enter data and run more than one slope problem within one computer run is important from a user's point of view and thus was evaluated. The importance of being able to handle the seismic coefficient and bilinear strength envelope was indicated in Part II. For this category, a dot indicates that the program has the indicated capability or that the manuals are available.

c. Input geometry. The ability to enter data from any quadrant of the X,Y coordinate system along with the ability to analyze slopes facing in either the +X or -X direction was evaluated. A dot for these two categories means that the program can handle this type of input. If the user can specify a tension crack as part of the input data, a dot was included in the matrix.

d. Type of failure surface. The type of failure surface associated with the considered analysis method is also indicated. The three types of surfaces are arc, wedge, and general.

e. Pore pressure input. This category is used to indicate if the program can handle various types of pore pressure data. The four types of data included in the criteria were reduced to three when the phreatic surface was considered a single piezometric line. If a program can handle multiple piezometric lines, then it will be able to handle one piezometric line. However, the reverse is not true. A dot indicates that the particular type of data input is currently available.

f. Searching options. This category is used to indicate if any searching technique is available for the type of failure surface evaluated. Since the search options are tied to the type of failure surface, the options evaluated are arc, wedge, and general. A dot indicates that one of the types of searching procedures is available for the corresponding type of failure surface.

g. Type and amount of output. This category indicates whether the user can specify the type and amount of results. The detailed output consists of enough data to perform a hand check. The brief output provides the data necessary to determine if the analysis is valid and to evaluate the completeness of searching for a critical surface. A dot indicates that the user can specify the amount of output. If some form of graphics output is available, then a dot was included under the graphics heading. The column dealing with negative side forces is filled when the program includes an error message that negative side forces have been encountered.

h. Type of computer. This category is used to indicate which computer is necessary to run the evaluated program. The current types that are generally available to the Districts are CDC,

Harris, and Honeywell. The availability of the program on a microcomputer was indicated. Usually the microcomputer necessary for the programs was an IBM PC or compatible. The column labeled as "other" usually indicated that the program would run on an IBM mainframe machine.

Evaluation Matrix

35. When the task group began evaluating the existing programs, they realized that there would not be a program that would meet all the criteria and that trade-offs would be necessary to select the interim programs for use until the ultimate program that meets all criteria is written. Those programs that include more analytical methods than were evaluated for this report were evaluated on only those options available for the chosen methods.

36. The matrix shown in Table 1 contains 13 programs. Of these programs, five perform the Bishop analysis, five the Spencer analysis, and five the Modified Swedish analysis (some do more than one type of analysis). There are only two programs that perform the wedge analysis as described in the slope stability manual (US Army Corps of Engineers 1970). The programs are listed below by the analysis which they perform.

Bishop analysis

SLOPE II
STABL
I0009 (CORPS library)
STABR
TSTAB

Spencer analysis

SLOPE II
TSTAB
TSLOPE
SSTAB2
UTEXAS

Modified Swedish analysis

SLOPE II
I0009 (CORPS library)
I0013 (CORPS library)
I0014 (CORPS library)
K.C.ARC

Wedge analysis

WEDGE 80
K.C.WEDGE

Only a few programs provide for interactive data entry and allow data to be entered from any quadrant. When hand checking is necessary, STABL, K.C.ARC, and K.C.WEDGE programs do not provide the detail output needed. Also there is a lack of programs with a generalized search technique.

PART IV: CONCLUSIONS AND RECOMMENDED PROGRAMS

Conclusions

37. Based on results of the slope stability computer program survey, the task group concluded the following:

- a. A program does not exist that meets all the criteria outlined in Part II.
- b. The program that comes closest to meeting all the criteria is a program being developed by Mr. S. G. Wright for the Texas Highway Department called UTEXAS.
- c. It would be faster and more cost effective to add the capabilities necessary to meet the criteria to UTEXAS instead of writing a new program.
- d. Until the capabilities are added to the Corps version of UTEXAS, the following programs are recommended for interim use:
  - (1) Bishop analysis -- STABR.
  - (2) Spencer analysis -- SSTAB2.
  - (3) Modified Swedish analysis (following Corps EM 1110-2-1902) -- K.C.ARC.
  - (4) Wedge analysis (following Corps EM 1110-2-1902) -- K.C.WEDGE.

Recommended Programs

38. Recommended interim programs are the best currently available to all Corps Districts and Divisions. The selection was based on the criteria met and general availability on accessible computers with no additional program surcharge. The user is not limited to these programs, but should be aware of additional costs or limitations involved. All the recommended interim programs are available in the CORPS library. The K.C.ARC and K.C.WEDGE programs are combined in a program called DGSLOPE. The information necessary to access these interim programs and to obtain user's manuals is provided in Appendix A.

39. All the interim programs have some shortcomings or limitations of which the user should be aware. These limitations deal with the type of failure surfaces, pore pressure data, search routines, and the method used for sudden drawdown calculations. The user is referred to the matrix in Table 1 and the individual program manuals for details about the programs.

REFERENCES

Bishop, A. W. 1955. "The Use of the Slip Circle in the Stability Analysis of Slopes," Geotechnique, Vol V, No. 1, pp 7-17.

Edris, E. V., Jr., and Vanadit-Ellis, W. 1982. "Geotechnical Computer Program Surveys," Miscellaneous Paper GL-82-1, US Army Engineer Waterways Experiment Station, Vicksburg, Miss.

Johnson, S. J. 1975. "Analysis and Design Relating to Embankments: A State-of-the-Art Review," Miscellaneous Paper S-75-3, US Army Engineer Waterways Experiment Station, Vicksburg, Miss.

Soriano, A. 1976. "Iterative Schemes for Slope Stability Analysis," Proceeedings, Second International Conference on Numerical Methods in Geomechanics, American Society of Civil Engineers, Vol 2, pp 713-724, Blacksburg, Va.

Spencer, E. 1976. "A Method of Analysis of the Stability of Embankments Assuming Parallel Inter-Slice Forces," Geotechnique, Vol 17, No. 1, pp 11-26.

US Army Corps of Engineers. 1970. "Stability of Earth and Rockfill Dams," Engineering Manual EM 1110-2-1902, US Government Printing Office, Washington, DC.

Whitman, R. V., and Bailey, W. A. 1967. "Use of Computers for Slope Stability Analyses," Journal of Soil Mechanics and Foundation Division, American Society of Civil Engineers, Vol 93, No. SM4, pp 455-498.

Wright, S. G. 1969. "A Study of Slope Stability and the Undrained Shear Strength of Clay Shales," Ph.D. thesis, University of California, Berkeley, Calif.

Wright, S. G., Kulhawy, F. H., and Duncan, J. M. 1973. "Accuracy of Equilibrium Slope Stability Analyses," Journal of Soil Mechanics and Foundation Division, American Society of Civil Engineers, Vol 99, No. SM10, pp 738-792.

Table 1

Slope Stability Computer Program Evaluation Matrix

EVALUATION ITEMS / PROGRAM	ANALYSIS METHOD				GENERAL						GEOMETRY			FAILURE SURFACE			PORE PRESSURE			SEARCHING OPTIONS			OUTPUT				COMPUTER CURRENTLY RUNNING ON					OWNER
	BISHOP	SPENCER	MODIFIED SWEDISH	WEDGE(EM 1110-2-1902)	PROGRAM DOCUMENTATION	USERS MANUAL	INTERACTIVE INPUT	MULTI-RUN CAPABILITY	SEISMIC CAPABILITY	BILINEAR STRENGTH	FAILURE IN BOTH DIRECTIONS	ALL QUADRANT	CAN TENSION CRACK BE INPUT	ARC	WEDGE	GENERAL	GRID PORE PRESSURE	Ru	MULTI-PIEZOMETRIC SURFACES	GENERAL	CIRCULAR	WEDGE	DETAILED OUTPUT	BRIEF OUTPUT	GRAPHICS	MESSAGE FOR NEGATIVE SIDE FORCES	C.D.C.	HARRIS	HONEYWELL	MICRO COMPUTER	OTHER	OWNER OF PROGRAM
SLOPEII	●	●	●		●	●	●	●	●		●		●	●	●	●	●	●	●		●		●	●	●	●	●				●	GEO-SLOPE PROGRAMMING
STABL	●				●	●		●	●					●	3	3		●	●		●	3		●	●		●			●	●	PURDUE UNIVERSITY INDIANA HIGHWAY DEPT OF TRANS
I0009	●		●			●			●	●	●			●							●		●	●		●	●	●	●			U.S. ARMY CORPS OF ENGINEERS
STABR	●				●	●		●	1	●		●	●	●				●	●		●		●	●		●	●	●		●	●	U.S. ARMY CORPS OF ENGINEERS
TSTAB	●	●			●	●		●	●	2			●	●			●	●	●		●		●	●	●	●	●			●		TAGA ENGINEERING SOFTWARE
TSLOPE		●			●	●		●	●	●			●	●	●	●		●					●	●	●	●	●			●		TAGA ENGINEERING SOFTWARE
SSTAB2		●			●	●		●	●	●	●	●	●	●	●	●	●	●	●		●		●	●	●	●	●					BUREAU OF RECLAMATION
UTEXAS		●				●		●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●			●	●	UNIVERSITY OF TEXAS
I0013			●			●	●	●	●	●	●			●							●		●	●	●	●	●	●	●			U.S. ARMY CORPS OF ENGINEERS
I0014			●			●	●	●	●	●	●				●	●				●		●	●	●	●	●	●	●	●			U.S. ARMY CORPS OF ENGINEERS
K.C.ARC			●		●	●	●	●	●	●	●	●									●			●	●		●	●	●			U.S. ARMY CORPS OF ENGINEERS
WEDGE 80				●		●			●	●					●		●	●	●				●	●	●				●			U.S. ARMY CORPS OF ENGINEERS
K.C WEDGE				●	●	●	●	●		●	●	●			●							●		●	●		●	●	●			U.S. ARMY CORPS OF ENGINEERS

NOTES: 1. Los Angeles District reports problems. 2. Bilinear for Spencer not Bishop. 3. Not performed in accordance with the four selected analysis methods

APPENDIX A: ACCESSING INTERIM PROGRAMS

1. All three recommended interim programs are available in the CORPS library on the CDC computer through the Corps TSP contract. The Corps library number for each program is as follows:

DGSLOPE	IØØ25
SSTAB2	IØØ26
STABR	IØØ27

To access a program, the following two commands are required:

```
GET,CORPS/UN=CECELB
BEGIN,,CORPS, Corps library number.
```

Only DGSLOPE is available on the Harris version of the CORPS library. The library number is the same as before, and the command to execute the program is

```
CORPS,IØØ25
```

2. User's manuals for each of the interim programs can be obtained by writing:

USAE Waterways Experiment Station
ATTN: WESTP-C/Rose Mary Peck
PO Box 631
Vicksburg, MS 39180-0631

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